# INTEGRITY OF JOINT STRUCTURES~THE KEY TO DAMAGE TOLERANCE

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## ABSTRACT

This paper deals with the effect of factors which affect the durability of various types of joint structure. On the fastener joint, effects of spike loads, corrosion environment, tightness, geometry and type of fastener on fatigue life are discussed. All results can be rationally explained by the tightness condition of the joint components. The effect of complex load by internal pressure, bending and torsion loads on the crack propagation behavior are also discussed. It was pointed out that the fatigue life under such loading conditions is controlled by ΔK using maximum principal stress. On the welded joint, effect of residual stress on fatigue crack propagation is discussed both experimentally and theoretically. For considering the behavior of widespread fatigue damage (WFD), the author proposed 2-parameter Weibull distribution function to simulate typical damage distribution based on the observation of the fractured components.

## 1 INTRODUCTION

Concerning the origins of structural failure, it is known that more than 80% are from the jointed components. Therefore, it is most effective to maintain the integrity of joint structure. In this paper, discussion is made on various factors affecting the integrity of the joint, the key of damage tolerance of the structure.

## 2 PROBLEMS OF STRUCTURAL INTEGRITY OF JOINT

Typical structural joints and their relevant problems on the joint integrity can be described as follows:

**Mechanical joints:** For such joint as lug, riveted or bolted joint, the causing factors of fatigue crack initiation and propagation are stress concentration by machined holes and notches, flaws and burr by poor machining, residual stress induced by clamping and fretting.

**Welded joints:** Major factors affecting the integrity are geometrical stress concentration, engulfed flaws and coarse grains at heat affected zone and residual stress.

**Adhesive joints**: The factors degrading the integrity of bonded joints are poor processing such as insufficient bonding by poor wetness among the laminates or in honeycomb sandwich panels, environmental cycles and discreteness of material property by bonding different materials.

## 3 FACTORS AFFECTING STRUCTURAL INTEGRITY OF FSTENER JOINT

Single lap joint fastened by countersunk or button head rivet is popular in the aircraft structures. The most important factor which affects the durability of the fastener joints is “tightness”. Load transmission mechanism of the joint depends on it. When the rivets are tight, load is transmitted mainly by the friction of mating plates. In this case, residual compressive stress suppresses the displacement around the rivet, and thus it suppresses the crack initiation and propagation even if there might exist initial imperfection at the edge of the fastener hole. On the other hand, when it is loose, the load is transmitted by the bearing force applied at the edge of fastener hole by the rivet itself. In this case, cracks are ready to initiate and propagate from the hole edge soon, regardless of the existence of initial imperfection.

Figure 1 shows the stress distribution around the fastener observed by thermo-elastic stress analyzer.1) Figure 1(a) is the case of single row fastener. Though the rivet was squeezed with standard force, highly concentrated compressive stress zone just below the rivet is observed. This implies the load is mainly transmitted by bearing force of rivet shank. In such a case, cracks are ready to initiate. On the other hand, Fig. 1(b) is the case of double row fastener. Contrary to the case of Fig. 1(a), no concentrated stress area is observed below the rivet. This means that the load is transmitted mainly by the surface friction of the mating plates. In this case, the role of the rivet is only to connect the plates tightly. The fastener also constrains the deformation near-by, and hence reduces the flaw opening displacement significantly and suppresses the crack initiation and propagation. Figure 1(b) also shows the load transmission rate of each row quantitatively. The top row carries 56% of total load, while the second and bottom row carries 44% of the load. This means that top row is always critical in the multi-row fastener as far as fatigue is concerned. When the fastener is not tight, fatigue cracks start from the center of the fastener hole, as if it were an open hole, and crack initiation life is relatively short. 2) However, as the tightness increases, the cracks start from the eccentric sites of the hole, and finally they start away from the hole after high fatigue cycle where the effect of residual compressive stress by squeezing the rivet diminishes. The main cause of these cracks is fretting.

### 3.1 Effect of overload and under-load

Effect of overload on fatigue life was studied by applying spike loads during constant amplitude fatigue test using single lap joint with double row fasteners3). The levels of spike loads were 80 and 90 % of tensile strength of the joint, respectively. The resulting fatigue life with and without overloads or under-loads is shown in Table 1. As is observed, the overload does not shorten the fatigue life. It rather extended the fatigue life. The high tensile overload is anticipated to produce the plastic deformation around the fastener hole, and it induces the residual compressive stress.

Effect of under-load, or compressive spike load, on fatigue life of single lap joint was also examined. Two cycles of compressive spike load were applied. The level of compressive load was 90 % of the buckling load. The effect of compressive spike load is complicated. For the countersunk fastener, these spike loads had no negative effect on the fatigue life, i.e., the compressive spike load did not necessarily loosen the fastener. For the button head fastener, however, these compressive spike loads gave unfavorable effect on the fatigue life. Although further experimental study is necessary, it is anticipated that the testing results may depend on the deformation mode under these spike loads. During compressive spike loads, the specimen exhibits considerable out-of-plane deformation. Either convex or concave mode from the manufactured side seemed to be the important factor for loosening the fastener and shortening the fatigue life.

### 3.2 Effect of initial imperfection at the fastener hole

Initial imperfection at the edge of fastener hole such as burr or tool marks can be the origin of fatigue crack. However, as long as tightness is maintained, those initial imperfections are not necessarily important factor for fatigue life. Tight fasteners suppress the relative displacement of the mating plates and flaws. The crack-like flaws never start propagating if the threshold cyclic displacement at the flaw tip necessary for crack extension is not obtained. The following example showed the complexity of the squeezing effect.

In order to study the bulging effect of fuselage structure, fatigue test was conducted by applying pneumatic pressure cycles[3)]. The specimen provided for the test was approximately one-third scale model of actual fuselage structure made of four curved panels. To specify the location of failure and also to observe the behavior of multi-site damage, initial flaws were introduced every other five holes at the top row fasteners of the center bay before squeezing. These flaws were not visible after the rivets were squeezed because they were hidden by the rivet head. After 80,000 pneumatic cycles, fatigue cracks were observed from several fasteners, but not from the fasteners with initial flaws. The final unstable failure occurred at 118,930 cycles shortly after some link-ups of neighboring cracks of the major crack. Contrary to our expectation, nothing happened at the fasteners with initial flaws till the final failure. Neither crack initiation nor propagation was observed there. This fact suggests that fatigue behavior is such sophisticated and sensitive phenomena and also fatigue tests using full scale model is important.

### 3.3 Corrosion fatigue and fatigue after corrosion

It is well-known that the corrosion damage at water surface of the off-shore structure is severer than that in the air or under-water. This is because the corrosion products, which are advantageous from the crack opening point of view, are ready to be washed away and fresh surfaces are continuously exposed in corrosive environment. In the corrosion fatigue, corrosion products of exfoliation type are continuously removed by cyclic loading. As a result, fatigue crack propagates faster than ambient conditions.

When fatigue test is conducted in ambient condition for the lap joint specimens immersed in the corrosion environment beforehand, the results are quite different compared with that of corrosion fatigue. Table 2 shows the relation between the immersion period and fatigue life ratios[4)]. The corrosive solution used was EXCO (ref. ASTM G-34). As presented in Table 2, the corroded specimens showed much longer life than virgin specimens. This phenomenon is inherent to the lap joint specimens. The reason for this is as follows: While the specimens are immersed, they received heavy corrosion damage proportional to the duration of immersion. However, as they were immersed in the still solution, the corrosion products remained there. These inflated corrosion products made the fastener much tighter than the joint specimens without immersed.

### 3.4 Effect of fastener row and fastening method

The effect of fastener row on fatigue life is apparent as shown in Table 3[3)]. This is because of not simply load bearing ratio of each row, but also suppression effect of out-of-plane deformation by multi-row fasteners.

### 3.5 Effect of complex loads

In the actual fuselage structure, various types of stress are induced during operation. Periodical pressurization induces cyclic hoop stress and longitudinal stress whose ratio is about 1 to 0.5. Rolling and pitching loads by maneuvering or turbulence induce torsion, shear force bending and pure bending to the skin structures. Consequently, it is important to evaluate the effect of these complex loads correctly when to estimate the fatigue life of the structure accurately. The following is the summary of the test results on the effect of secondary loads on the fatigue behavior of the fuselage structure subjected to the internal pressurization cycles and/or torsion loads. In the case of combination of shear force bending and internal pressure cycles, the resultant principal stress and its direction can be evaluated by Eqs. (1), (2).

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ 0 \end{Bmatrix} = \begin{bmatrix} \cos^2\theta_1 & \sin^2\theta_1 & 2\sin\theta_1\cos\theta_1 \\ \sin^2\theta_1 & \cos^2\theta_1 & -2\sin\theta_1\cos\theta_1 \\ -\sin\theta_1\cos\theta_1 & \sin\theta_1\cos\theta_1, \cos^2\theta_1-\sin^2\theta_1 & \end{bmatrix} \begin{Bmatrix} \sigma_{hoop} \\ \sigma_{axial} \\ \tau \end{Bmatrix} \tag{1}$$

$$\theta_1 = \frac{1}{2}\tan^{-1}\left(\frac{2\tau}{\sigma_{hoop}-\sigma_{axial}}\right) \tag{2}$$

Table 4 shows the test results. It is apparent that higher principal stress resulted in shorter fatigue life. And the fatigue cracks from the fastener holes initiated and propagated perpendicular to the maximum principal stress for both cases. It is concluded that the fatigue behaviors of structural components under complex fatigue loads can be estimated by evaluating the principal resultant force and its direction.

## 4 FATIGUE STRENGTH OF WELDED JOINT

### 4.1 Factors affecting the fatigue strength

The influencing factors to the integrity of the joint can be categorized into three groups as shown below.

**4.1.1 Mechanical factors related to the welding process;** Blow holes, embedded slugs and unbonded surface are categorized as mechanical defects. Blow holes are rather easy to detect by X-ray inspection. And it is generally considered to be less hazardous because of their spherical shape, if they are relatively small. On the other hand, embedded slugs and unbonded surface are often overlooked by X-ray or other NDI techniques. They are generally penny-shaped, and thus they are hazardous.

**4.1.2 Metallurgical factors due to heat input;** The intensified local heating and cooling cycle causes re-crystallization near the bonded zone. The heat affected zone (HAZ) with coarse grain generally exhibits less elongation and toughness and different mechanical properties compared with base metal. In order to avoid the un-expected failure by low toughness, heat treatment is often conducted after welding. However, we have to pay attention on the relation between heat treatment temperature and mechanical properties as they sometimes show drastic change by the small difference of temperature.

**4.1.3 Residual stress by welding;**

### 4.2 Effect of residual stress on fatigue crack propagation

It is known that residual stresses have a harmful effect on the fatigue behavior, especially on fatigue crack propagation. The effect of residual stress can be considered as the effect of mean stress whose magnitude is the function of the distance from the weld line. The effective stress intensity factor ($Keff$) of a crack in the field of residual stress can be presented as:

$$Keff = Kapp + Kres \tag{3}$$

where, $Kapp$ is K by remotely applied stress and $Kres$ is K by residual stress. For simplicity, when the crack is a small internal crack, the crack propagation is the function of the effective stress intensity factor range shown by Eq. (4)[3].

$$\Delta K_{eff} = \Delta K_{app} + K_{res} = \Delta K_{app}(1+\frac{\sigma_0}{\Delta\sigma}F_{res}) \tag{4}$$

where, $\sigma_o$ : maximum residual stress, $Fres$: correction factor of a crack by residual stress (see, ref.5 for variety of cracks perpendicular to the welding joint). The effectiveness of Eq. (4) is verified by comparing the testing result conducted by Glinka et.al.[6] as presented in Fig. 2.

## 5 A PROPOSAL TO FULL-SCALE DAMAGE TOLERANT EVALUATION

Full-scale fatigue test is recommended to guarantee the structural integrity during operation. In the case of aircraft structure, twice of economical design fatigue life and additional one life of damage tolerant test are generally recommended. The objective of the full-scale damage tolerant test is to assure the integrity against unpredicted and time-depended damage such as incidental damage by FOD and corrosion. Therefore, full-scale damage tolerant test is conducted by assuming the existence of initial damage in the critical component of the structure. In this conjuncture, the assumption of damage distribution should be realistic as much as possible, because it affects the test results significantly. Equation (5) is a proposal for the flaw distribution based on the damage observation of fatigue fractured component in fatal accident.$^{1)}$

$$f(t) = \frac{At^{-0.82}}{t_0}\exp(-\frac{t^m}{t_0}) \qquad (5)$$

where, A: constant, $t_0$: 0.66 (scale parameter), m: 0.18 (shape parameter), t= length/ pitch of flaws.

## 6 CONCLUDING REMARKS

The effect of mechanical, geometrical and environmental factors that are considered to affect the fatigue life of the various type of joint structure are listed and discussed. On mechanical joint, it was pointed out that tightness is the key to the durability of joint structures. The effects of complex loads on fatigue characteristics were reasonably evaluated by maximum principal stress and its direction.

**References**

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Table 1 Effect of spike load on constant amplitude fatigue strength of single lap fastener joint

| Type of rivet* | spike load | | | Nf, ave.*** | Note |
|---|---|---|---|---|---|
| | Magnitude | No. of load | No.,appl** | | |
| B | - | - | - | 322,000 | reference |
| B | 0.8σu**** | 2 | 40,000 | | |
| | 0.9σu | 1 | 66,400 | >440,000 | |
| B | 0.9σbuckl***** | 2 | 80,000 | 161,000 | |
| C | - | - | - | 71,000 | reference |
| C | 0.9σbuckl | 2 | 80,000 | 250,000 | |

*B: button head, C: countersunk, **number of const. fatigue cycles when spike loads were applied

***:fatigue life, **** tensile strength, ***** buckling strength

Table 2 Normalized life of EXCO corroded single lap joint

| t(mm) | immersed period (week) | | | | |
|---|---|---|---|---|---|
| | 0 | 2 | 4 | 8 | 16 |
| 1 | 1 | 3 | 16 | 8 | 3.2 |
| 2 | 1 | 3 | 3.5 | 4 | 6 |

Double row countersunk fastener

No immersion, Nf: 120,000(t=1), Nf: 72,000(t=2)

Table 3 Fastener row and fatigue life

| Type of rivet* | Row | Nf** |
|---|---|---|
| B | 1 | 39,020 |
| B | 2 | >400,000 |
| C | 1 | <28,000 |
| C | 2 | 368,000 |

Fatigue load (54±42)MPa

Specimen: t=1mm, W=300mm

* B: button head, C: countersunk

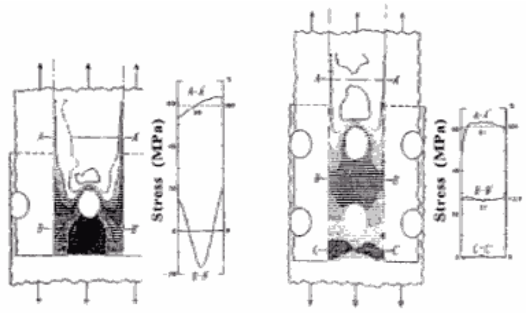
** Fatigue life

Table 4 Effect of combined fatigue load

| Type of load | Ni* | Nf** | Note |
|---|---|---|---|
| A | 90,000 | 118,930 | cyclic internal pressure only |
| B | 45,000 | 79,515 | internal pressure+ bending |

*: Crack initiation life, **: Total failure life

Cyclic internal pressure caused (54±42)MPa at skin center.



(a) Single row (b) Double row

Figure 1 Stress distribution around rivets observed by thermo-elastic analyzer

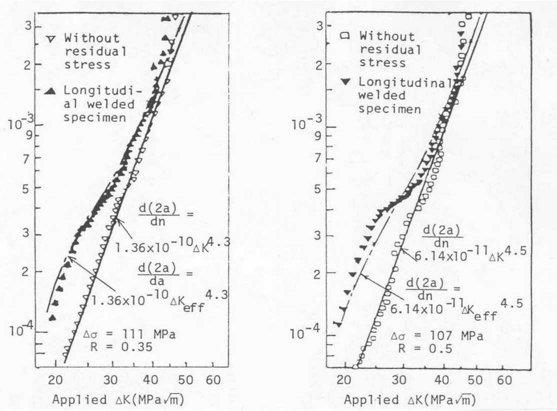


Figure 2 Comparison of crack growth rate by *Keff* estimation and test data(6)